Hierarchical Biosilicates by the 3-D Replication of Block Copolymer Templates in Supercritical Fluids

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Abstract

Unique methods for the encapsulation of biologically-derived materials within ordered mesoporous silica films, the preparation of mesoporous silica films using a biodegradable template system, and the preparation of thermally stable, mesoporous silica spheres with tunable diameters ranging from 40 nm to 560 nm, narrow size distributions on the order of 10%, surface areas greater than 1000 m^2/g, and pore volumes on the order of 1 cc/g were demonstrated. The stable spheres were synthesized using tetraethylorthosilicate at room temperature and near-neutral pH using cysteamine as the catalyst and cetyltrimethylammonium bromide (CTAB) as the structure directing agent in a mixed water and ethanol system. The pore walls were resistant to collapse at temperatures exceeding 750 °C in air and upon hydrothermal treatment in boiling water for over 100 hours. Silica formed using bio-inspired small molecule catalysts including cysteamine, glutathione and methionine alone or in combination provided highly condensed silica networks at room temperature over a broad range of pH as evidenced by ^{29}Si NMR.

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14. ABSTRACT

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Summary

Unique methods for the encapsulation of biologically-derived materials within ordered mesoporous silica films, the preparation of mesoporous silica films using a biodegradable template system and the preparation of thermally stable mesoporous silica spheres of prescribed diameters at ambient temperature using a simple one pot synthesis were demonstrated.

Ferritin was encapsulated within mesoporous silica films by the 3-D replication of block copolymer templates. Pluronic^{tm} F127 (PEO_{105}-PPO_{70}-PEO_{105}) templates containing horse spleen ferritin and organic acid were prepared by spin coating. Phase selective deposition of silica within the block copolymer was conducted by exposure of the template films to solutions of tetraethylorthosilicate (TEOS) in supercritical carbon dioxide**.** Ordered mesoporous silica glasses containing encapsulated magnetic nanoparticles were obtained by calcination of the composite**.**

Thermally stable, mesoporous silica spheres with tunable diameters ranging from 40 nm to 560 nm, narrow size distributions on the order of 10%, surface areas greater than 1000 m^2/g, and pore volumes on the order of 1 cc/g were synthesized using a one-pot technique under mild conditions. The spheres were synthesized using TEOS at room temperature and near-neutral pH using cysteamine as the catalyst and cetyltrimethylammonium bromide (CTAB) as the structure directing agent in a mixed water and ethanol system. The pore walls were resistant to collapse at temperatures exceeding 750 °C in air and upon hydrothermal treatment in boiling water for over 100 hours. Sphere size was tunable by altering the initial proportions of ethanol, CTAB, and/or TEOS in the reaction.

Silica gels and monoliths were formed using bio-inspired small molecule catalysts including cysteamine, glutathione and methionine as catalyst alone and in combination in deionized water using tetraethylorthosilicate (TEOS) as precursor over a broad range of pH including neutral and near neutral conditions at ambient temperature. These simple catalyst systems provided highly condensed silica networks as evidenced by ^{29}Si NMR.

The synthesis of mesoporous silica using a biodegradable poly(lactic acid)–b–poly(ethylene oxide)–b–poly(lactic acid) triblock copolymer template with cysteamine as catalyst was demonstrated.

1. Introduction

The formation of hierarchical silica structures in nature provides remarkable illustrations of structural control through templating. Capturing this ability in the laboratory will provide enabling routes to nanostructured materials, elements and devices. Recent work has demonstrated the formation of biosilica using biological and biomimetic catalysts at mild conditions. However, to date the realization of fine structural control at multiple length scales necessary to create well organized structures has remained elusive. By comparison synthetic methods based on sol-gel chemistry that employ cooperative assembly in aqueous media can yield ordered silicates, but typically employ harsh conditions, extremes in pH, and elevated temperatures that are not compatible with biological systems. Realization of the full potential of biosilica-based materials and devices requires resolution of these issues. In this project, we investigated alternative processes to produce defined hierarchical silica structures using three unique scenarios. The first involves the encapsulation of biological payloads, namely ferritin, in well organized mesoporous silica films using a process developed in our labs in which the three-dimensional structure of block copolymer templates is replicated in metal oxides. The process involves the supercritical CO_2-assisted infusion and phase selective condensation of silica precursors within one domain of the pre-organized block copolymer template. The second involves replacement of the surfactant-based template systems used in typical preparations with a biodegradable template that can be removed at mild conditions. Such an approach enables removal of the template at conditions that do not harm labile payloads and provides a mechanism for controlling the release of payloads encapsulated within the mesoporous silica/template composite. This strategy was applied to both the 3-D replication strategy in CO_2 and more conventional synthetic techniques were approached using aqueous routes. The third route involves the preparation of stable mesoporous silica films and spheres with precisely prescribed structures at conditions of mild temperature and near neutral pH using bio-inspired catalyst systems to enable the encapsulation of sensitive payloads. This work was also shown to produce exceptionally stable silica structures. Each of these approaches is useful for a variety of applications including selective catalysis and preparation of on-chip recognition elements for biosensors and medical diagnostics. Finally, we examine the ability to tune pH during the synthesis of silica using mixtures of bio-inspired catalysts.

2. Background

Our group has developed a robust strategy for mesoporous film fabrication that involves the three-dimensional replication of block copolymer templates using supercritical carbon dioxide as a delivery medium.[2-7] An amphiphilic block copolymer is first deposited onto a substrate by spincoating from a solution containing an organic acid catalyst. Inorganic precursors are then infused into the pre-organized copolymer thin films using supercritical CO_2 as the carrier. Swelling the template in supercritical carbon dioxide significantly enhances diffusion within the polymer film,[8,9] without disrupting phase segregation.[10,11] Precursor condensation then occurs exclusively within the acid catalyst-doped hydrophilic phase and removal of the template yields mesoporous inorganic structures. Separation of template assembly from inorganic network formation offers a number of advantages, including the ability to select templates and precursors independently by elimination of the requirement of cooperative assembly. Moreover, such an approach provides opportunity for doping of the template with functional material prior to silica network formation. This is beneficial for many biological systems, since they are usually soluble in aqueous media. Our recent templates of choice include Pluronic poly(ethylene oxide)-

poly(propylene oxide)-poly(ethylene oxide) triblock copolymers. The use of PEO as one of the blocks is beneficial for doping the templates with biological additives.

The use of strong acid or base as catalyst for silica condensation during the synthesis of mesoporous materials can be a serious limitation for the incorporation or encapsulation of bioactive species. Recent work inspired by the observation that robust hierarchical silica structures are synthesized in nature under ambient conditions at near-neutral pH provides avenues for resolving this difficulty. Cha, *et* al.[12,13]and Sumper, *et* al.[14-19] discovered a number of potential silica catalysts derived from or based on proteins and polypeptides derived from diatom shells. Naik *et al.* [20] and Kroger *et al.* [15] showed that the R5 peptide, an extract from a diatom shell, was capable of catalyzing amorphous silica formation from TMOS under ambient conditions. Synthetic copolypeptides were shown to precipitate silica from tetraethyl orthosilicate (TEOS) as well.[13] Mukherjee[21] showed that mesoporous silica spheres can be templated from TEOS using simple sugars. Roth *et al.*[22] examined several small molecule catalysts containing thiol, hydroxyl, primary amine, and ammonium groups specific to these diatom peptides, such as R5, that could potentially catalyze silica formation. Cysteamine ($HSCH_2CH_2NH_2$) titrated to neutral pH with HCl was found to be the most active of the small molecule catalyst systems tested. Cysteamine is an attractive alternative to common HCl or ammonium based silica catalysis methods as it is possible to obtain silica at both mildly basic pH (approximately 9.5) and ambient temperature. These mild reaction conditions to form silica using cysteamine could allow for in situ encapsulation of condition sensitive payloads such as enzymes within silica.

3. Objectives of this Work

Objectives of this work include:

1. The encapsulation of biomolecules including the use of ferritin as a model system within well-ordered mesoporous silica films prepared by the 3-D replication of doped block copolymer templates.

2. The development of a biodegradable template system for ordered mesoporous silica films for applications in controlled release.

3. The preparation of mesoporous silica nanospheres of controlled diameter in aqueous solution at near neutral pH.

4. The synthesis of silica at conditions of tunable pH using mixed bio-derived catalyst systems.

4. Accomplishments/New Findings

4.1 Fabrication of Ordered Mesoporous Silica Films with Encapsulated Iron Oxide Nanoparticles through Supercritical CO_2 Infusion of TEOS into Ferritin Doped Block Copolymers[23]

There has been a great deal of interest in the fabrication of defect-free mesoporous silica thin films for potential device applications including ultra-low dielectric constant thin films for

microelectronics, catalyst supports, sensors and separations media.[24-26] The incorporation of functionality within a mesoporous silica thin film through encapsulation of active materials significantly increases the utility of these materials.[27] For example, the immobilization of enzymes encapsulated in silica particles and thin films has been investigated for improved enzyme efficiency and stability. Horseradish peroxidase (HRP) encapsulated in silica has been shown to have an increased stability in organic solvents.[28] Trypsin and acid phosphatase have also been encapsulated in an inorganic silica network.[29, 30]

Through a collaboration with Rajesh Naik at the Air Force Research Laboratories, we demonstrated a straightforward strategy for the encapsulation of active nanoparticles within mesoporous silicas using horse spleen ferritin as a model system. Ferritin is a spherical iron storage protein typically found in the spleen or liver of living organisms that has been widely studied for its interesting magnetic properties.[31-33] Structurally, ferritin is comprised of a complex protein membrane shell, apoferritin, surrounding an iron oxide-like core. As ferritin is hydrophilic, so long as its protein outer-shell is intact, the iron-containing protein will selectively partition to the hydrophilic block when mixed with an amphiphilic copolymer. Solutions of Pluronic^{TM} F127 (PEO_{105}-PPO_{70}-PEO_{105}) containing horse spleen ferritin and p-toluene sulfonic acid were spin-coated onto silicon test wafers. Phase selective deposition of silica within the ferritin containing block copolymer was conducted by exposure of the template films to solutions of tetraethylorthosilicate in supercritical carbon dioxide. Silica network formation occurs exclusively in the hydrophilic block due to partitioning of the acid catalyst to the PEO rich domains during spin coating. The resulting ferritin-doped material can then be used to produce a mesoporous magnetic glass. Upon high temperature calcination, a mesoporous silica thin film containing iron oxide remains as the both the copolymer and apoferritin shell are removed. A schematic detailing this procedure is provided in Figure 1. Detailed procedures are available elsewhere.[23, 34]

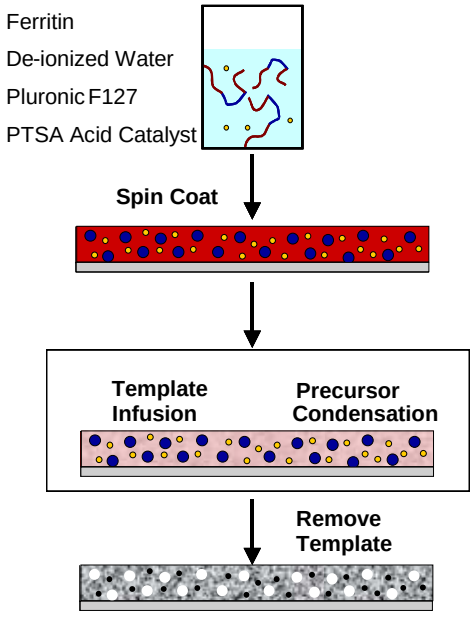

Figure 1: Schematic detailing the formation of ferromagnetic mesoporous silica thin films. The red continuous domain represents PEO, which is doped with ferritin (yellow spheres). The blue PPO domains are removed during calcination as is the apoferritin shell, leaving magnetic iron oxide particles (black) embedded in the mesoporous silica film.

The iron oxide doped silica thin film structure was verified by x-ray diffraction (XRD) and transmission electron microscopy (TEM) and magnetic properties were determined by SQUID magnetometry and magnetic force microscopy (MFM).

TEM images of the well-ordered iron oxide doped silica thin films are provided in **Figure 2** for ferritin loadings of 1 wt% (A), 5 wt% (B), and 10 wt% (C). For the 1 wt.% film (Figure 2A), the pore order was disrupted slightly relative to un-doped mesoporous films prepared previously using a similar protocol. The films prepared using templates containing 5 wt.% ferritin appear to exhibit better order than those prepared with 1 wt%. This observation is supported by small angle XRD analysis, wherein the appearance of a second order reflection as the ferritin concentration is increased from 1 wt% to 5 wt% is apparent (**Figure 3**). Further, as ferritin concentration in the film is increased, there is a distinct increase in *d*-spacing that arises from expansion of the PEO domains of the template film to accommodate the ferritin particles. The ratio of the peak positions of first and second order reflections, 1:√2, suggest that a cubic phase cylindrical morphology is maintained within the films, which is consistent with the TEM micrographs. Further increase in ferritin concentration to 10 wt% appears to yield a less ordered silica structure, as the increased concentration of ferritin may frustrate template self-assembly.

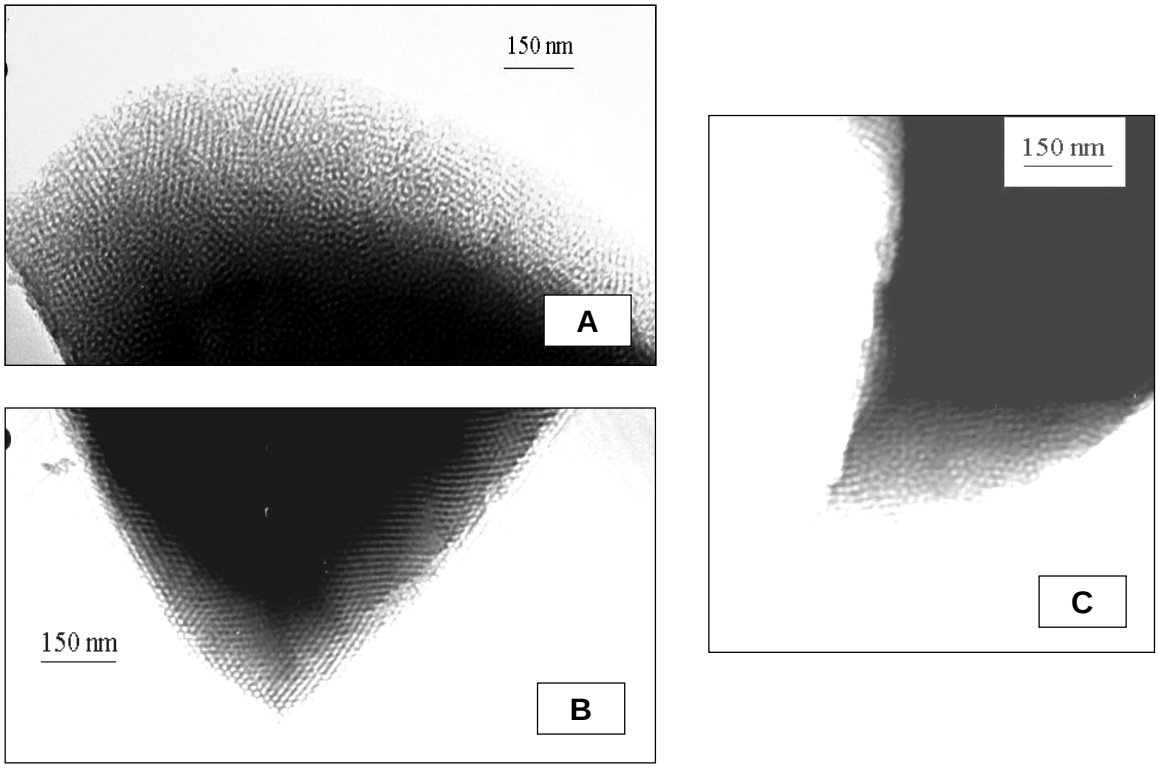

Figure 2. TEM images of ferritin-containing samples at the specified ferritin concentrations: A) 1 wt% ferritin loading; B) 5 wt% ferritin loading; C) 10 wt% ferritin loading. Reaction conditions: TEOS infusion at 40°C, 126 bar; calcination for 6 hours at 400°C

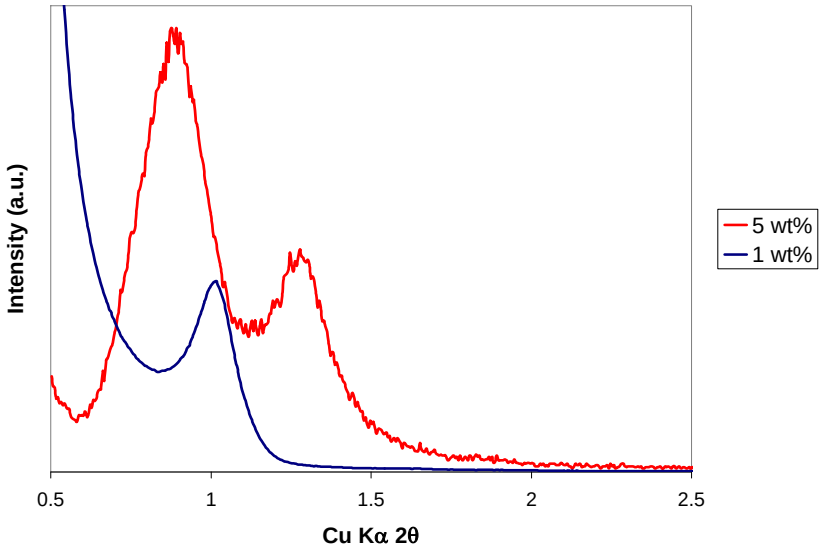

Figure 3: Small angle XRD of 1 wt% and 5 wt% ferritin-containing silica films

The inherent magnetic properties of ferritin were confirmed to be present in both the as-spun Pluronic F127, PTSA, and ferritin films and in the calcined mesoporous silica films with encapsulated ferritin. An MFM image of the as-spun template film is provided in **Figure 4**. SQUID magnetometry measurements indicate that the iron oxide doped mesoporous thin films maintained magnetic character post supercritical CO_2 processing and post calcination.

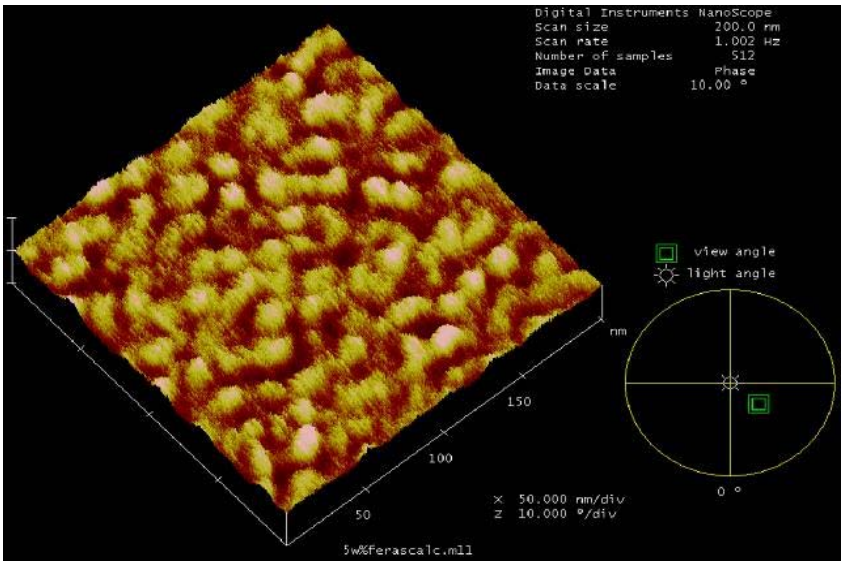

Figure 4: MFM image of an as-spun template film indicating even dispersion of ferritin.

In conclusion, an easy route to the preparation of ferromagnetic mesoporous thin films was demonstrated. A similar route to the one presented herein could be pursued to form mesoporous silica thin films with different functionalities.

4.2. Simple Method for the Fabrication of Mesoporous Silica Templated by a Biodegradable Block Copolymer at Neutral pH

It is desirable to prepare doped silica films using biodegradable templates that can be used to modulate the release of encapsulants. In this work, mesoporous silica particles were prepared at near-neutral pH and ambient temperature using biodegradable poly(lactic acid)–b–poly(ethylene oxide)–b–poly(lactic acid) [PLA-PEO-PLA] triblock copolymer templates and a bio-inspired catalyst, cysteamine. Silica formed under mild conditions can be used for in-situ encapsulation of condition-sensitive active particles. As PLA is biodegradable, this block can be easily removed, post silica condensation, leaving open pores within the silica network. This degradation mechanism would allow for the slow release of a silica-trapped drug or molecule. Also, a therapeutic may be incorporated directly into the hydrophobic PLA domains for slow release while PLA degrades.

Mixtures of water-insoluble micelles of PLA-PEO-PLA, cysteamine, and TEOS in deionized water were allowed to self-assemble at ambient temperature. Cysteamine is believed to selectively partition to hydrated hydrophilic PEO rich domains the block copolymer. The PLA blocks appear to serve as an effective porogen. Details of the synthesis are available elsewhere.[34] TEM images of the block copolymer silica composites are provided in **Figure 5.**

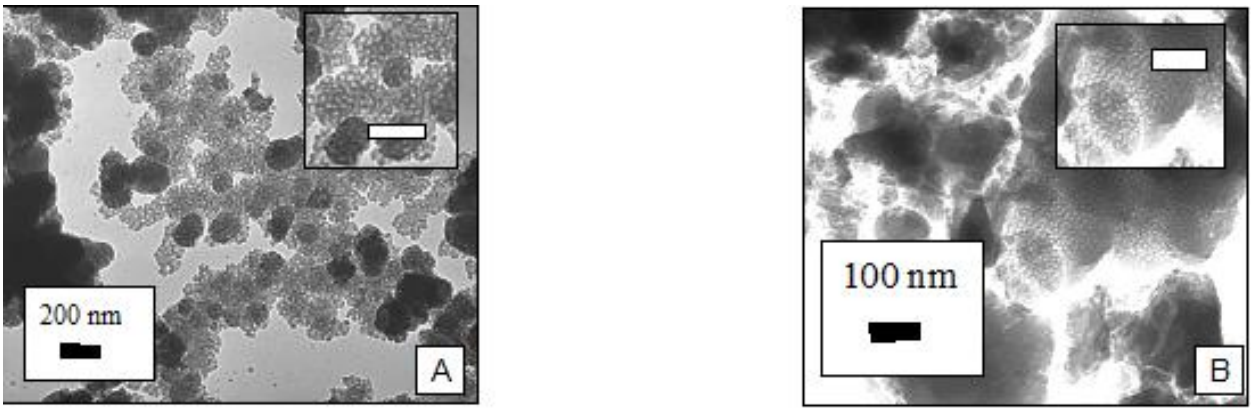

Figure 5: TEM micrographs of PLA-PEO-PLA and silica composites A: 64% PEO, PLA-PEO-PLA, B: 86% PEO, PLA-PEO-PLA

SAXS characterization (**Figure 6**) of these composite materials verifies that, by changing the molecular weight and composition of the copolymer, pore shape and size, in degraded specimens, is tunable. Both polymers measured herein have a PEO M_n of 8800. The 64% PEO sample has a PLA M_n of 5040, whereas the 86% PEO sample has a PLA M_n of 1440.

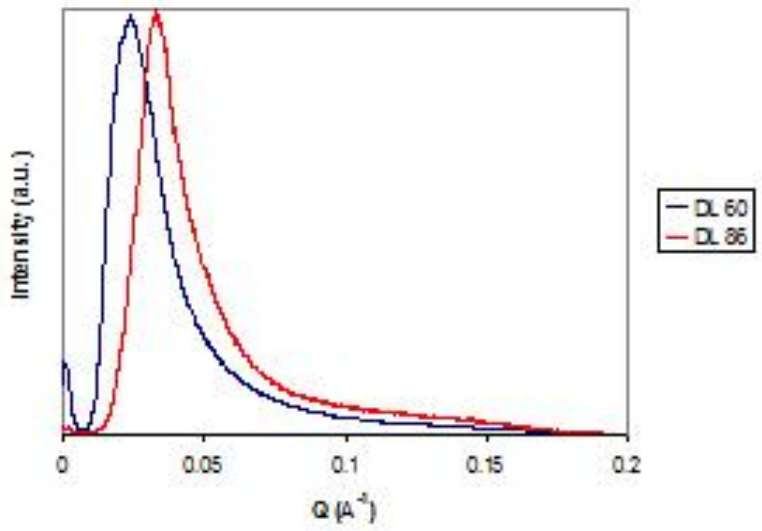

Figure 6: SAXS data for biodegradable block copolymer and silica composites, DL60 (blue line) indicates 64% PEO, PLA-PEO-PLA and has a d-spacing of 25 nm, DL86 (red line) represents 86% PEO, PLA-PEO-PLA and has a d-spacing of 18 nm.

In this work, mesoporous silica was formed using both a bio-inspired catalyst and a biodegradable block copolymer under mild synthesis conditions. It was shown that this system has potential in drug encapsulation and sustained release. Further, as PLA domain size and shape was shown to be readily changed by altering either the block copolymer M_w or composition, payloads with varying size can be encapsulated.

4.3. Thermally Stable Mesoporous Silica Spheres Synthesized from TEOS using Small Bi-functional, Biomimetic Catalysts at Room Temperature and Near-neutral pH[35]

The synthesis of precisely defined mesoporous silica spheres is of interest for a broad range of applications, including catalysis, sustained release/controlled delivery and sensors. In addition to control of the architecture, there are additional application specific challenges that must be overcome. These include synthesis at mild conditions to accommodate labile payloads and the formation of thermally and hydrothermally stable silicas for applications in catalysis and separations. In this work, we addressed both challenges through the development of a simple, one pot technique for the fabrication of stable mesoporous silica spheres of precisely controlled diameter at mild conditions and near neutral pH. The mesoporous silica spheres (**Figure 7**) were synthesized from TEOS at room temperature under mildly basic conditions using cysteamine as a catalyst and CTAB as a structure directing agent (SDA). Details of the synthesis are available elsewhere.[35] The silica spheres (cys-spheres) were found to be relatively monodisperse upon characterization by electron microscopy and highly condensed upon characterization by ^{29}Si MAS NMR. Moreover, silica sphere size was shown to be easily controlled by altering the initial concentration of ethanol allowing for synthesis of spheres ranging from 30 nm to 560 nm in diameter. Lastly, the silica spheres were found to have a very large surface area, upwards of 1000 m^2/g, with pore volumes on the order of 1 cc/g. The use of mild synthesis conditions is promising for the encapsulation of biomolecules. Additional detail is provided in section 4 of this report. Here we focus attention on a more surprising and potentially very useful result; namely the discovery that spheres produced by this technique exhibit excellent thermal and hydrothermal stability.

Among the most common mesoporous silicas are the MCM and SBA types templated from C_nTAB and PEO-PPO-PEO triblock copolymers, respectively. As is expected, MCM-type silica templated from C_nTAB contains much thinner mesopore walls than SBA-type silica templated from a triblock copolymer. Thickness, along with degree of surface condensation, thermal pretreatment, and presence of surfactant or salts contribute to the thermal and hydrothermal stability of pore walls in mesoporous silicas. Cys-sphere pore walls are comparable to those of MCM-41 silicas as both are templated from cetyltrimethylammonium bromide (CTAB) and have pore sizes of approximately 2 nm in diameter. To examine the thermal stability of the cys-sphere pore walls, uncalcined portions without thermal pretreatment were calcined at 550 °C to remove CTAB and any other residual organics prior to thermal treatment at temperatures upwards of 750 °C and hydrothermal treatment in boiling water. Even without thermal pretreatment, the silica spheres (Cys-1, Cys-2, and Cys-3) synthesized using cysteamine as a catalyst showed exceptional thermal stability compared to MCM-type and even SBA-type silicas (**Table 1**).

Table 1

BET surface area (m^2/g) from nitrogen adsorption measurements. Cys-1, Cys-2, and Cys-3 were both formed using the same procedure using cysteamine as a catalyst. MCM-41 and SBA-15 data reproduced from Cassiers. [1]

T (°C)	Cys-1	Cys-2	Cys-3	MCM-48[1]	MCM-41[1]	SBA-15[1]
550	921	-	1560	1,433	1,128	632
650	825	952	1020	1,248	1,114	561
750	-	**696**	**855**	**108**	**403**	446
800	**408**	-	**564**	-	-	-

The structural underpinnings of the thermal stability of the Cys-spheres can be further characterized by cross polarization (CP) ^{1}H- ^{29}Si NMR. ^{1}H- ^{29}Si CP NMR can measure the degree of condensation at the surface of a silica sample by enhancing the ^{29}Si signal through magnetization transfer from a proton to the ^{29}Si isotope. Further, by increasing the contact time, CP NMR can provide the degree of silica condensation at increasing depth into the sample. CP NMR data between cys-spheres and mesoporous spheres using ammonium hydroxide and the method of Grun[36] were compared.

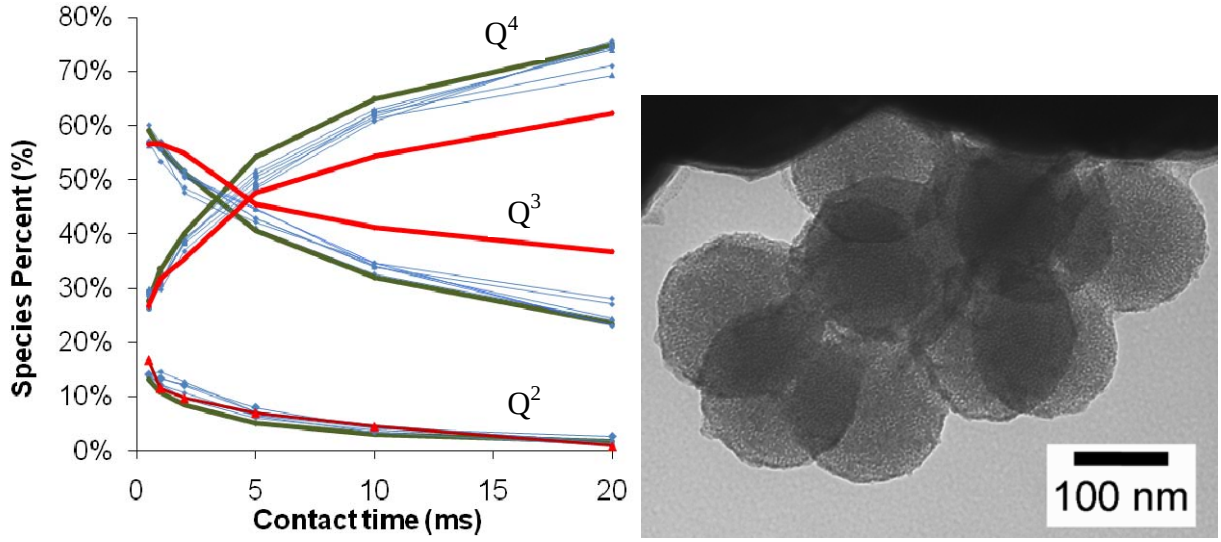

Figure 7: Left: Deconvoluted CP NMR for uncalcined cys-spheres (blue lines) and Grun spheres (bold red lines), Right: TEM image of mesoporous cys-spheres. Green lines indicate cys-sphere sample with highest amount of TEOS loading.

Deconvoluted CP NMR data presented in Figure 1 (left) clearly shows the difference in degree of surface silica condensation between uncalcined cys-sphere samples and uncalcined Grun [36] spheres, which were synthesized using ammonium hydroxide as a catalyst for TEOS hydrolysis. As Grun spheres have a similarly sized pore wall compared with cys-sphere samples, it can be stated that the cys-spheres are more highly networked at the surface. The high degree of silica condensation prior to thermal treatment at the surface for cys-sphere samples from CP NMR data provides rationale for the large surface area measurements gleaned from the nitrogen adsorption data on samples calcined at temperatures as high as 800 °C (**Table 1**). CP NMR was also used to measure degree of surface silica condensation for cys-sphere samples subject to thermal treatment at 550 °C and 650 °C (**Figure 8**).

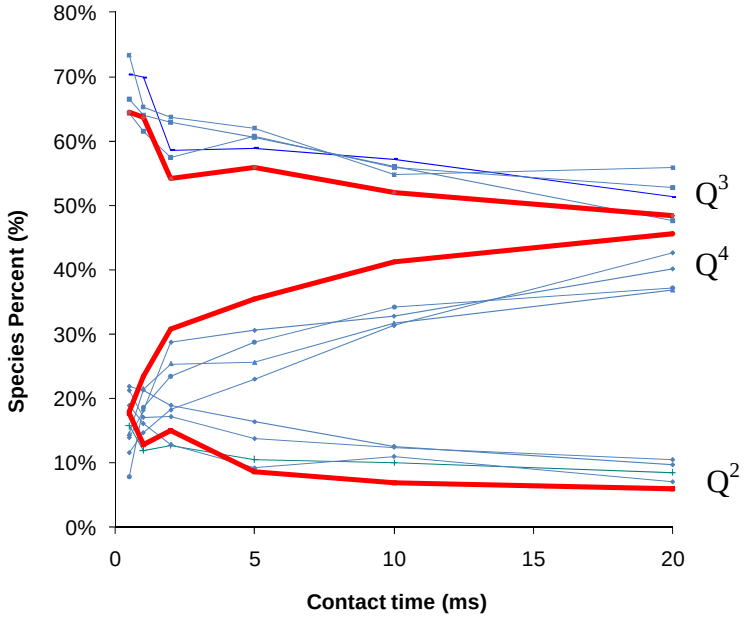

Figure 8: CP NMR data for 550 °C and 650 °C calcined cys-spheres (bold red lines indicate 650 °C calcination)

CTAB, which was used in this study as both a porogen and structure-directing agent, is removed from pores at temperatures greater than 500 °C. As a result of CTAB removal, it was found that the Q^3 species, or silanols, were the predominant species at each contact time measured. It was also seen that cys-sphere samples calcined at 650 °C were more condensed at the surface than those calcined at 550 °C. This indicates a combination of pore collapse and surface annealing upon thermal treatment, which correlates to the decrease in BET surface area seen in **Table 1**. It should be noted, however, that cys-sphere samples maintained a larger amount of surface porosity on high temperature thermal treatment than MCM-type silicas synthesized by typical means.

The range of obtainable cys-sphere diameters was 30-560 nm. Cys-sphere diameter was found to be largely dependent on the amount of ethanol present in the reagent mixture. It has also been seen that small changes in the amount of TEOS or CTAB influences cys-sphere size. **Figure 9** summarizes the relationship between cys-sphere size and initial mixture component concentration.

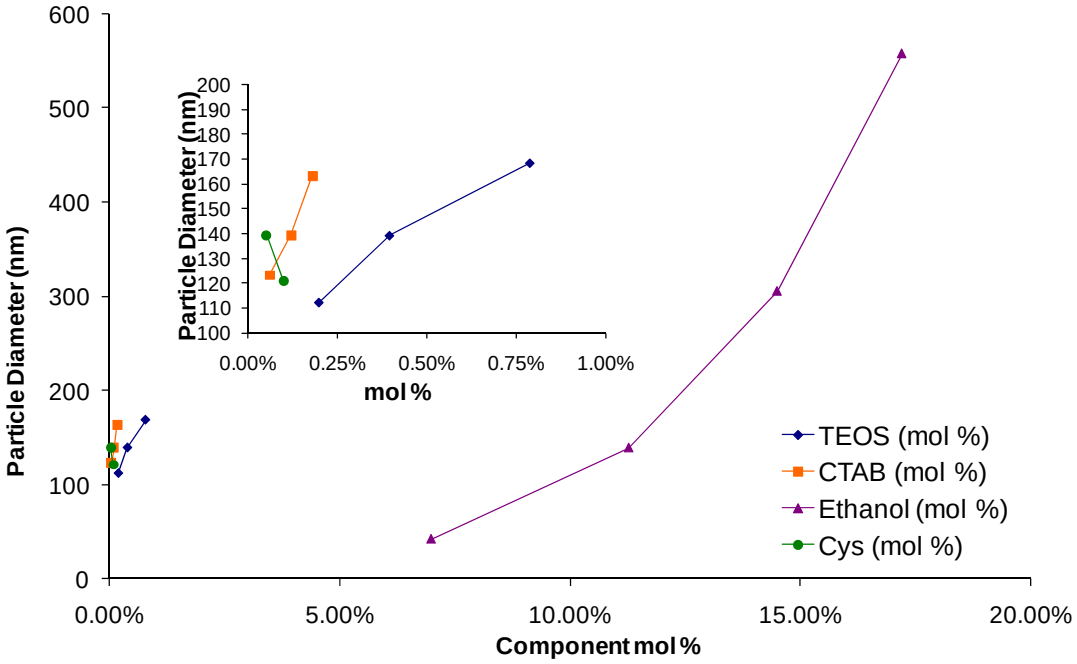

Figure 9: Dependence of cys-sphere diameter on concentration variation of the indicated component in the reaction mixture.

Through the use of a mixed L-glutathione and cysteamine catalyst system, highly condensed silica spheres were synthesized at neutral pH and room temperature. CP NMR data presented in **Figure 10** indicates that spheres synthesized using the mixed catalyst system at pH=7 were either equally condensed or more highly condensed at the surface than spheres formed under slightly alkaline conditions using only cysteamine. ^{29}Si MAS single pulse NMR data shows a greater degree of network condensation for spheres synthesized using the neutral technique in the bulk. These observations could be a consequence of the slower reaction kinetics at neutral pH than those at acidic or basic conditions.

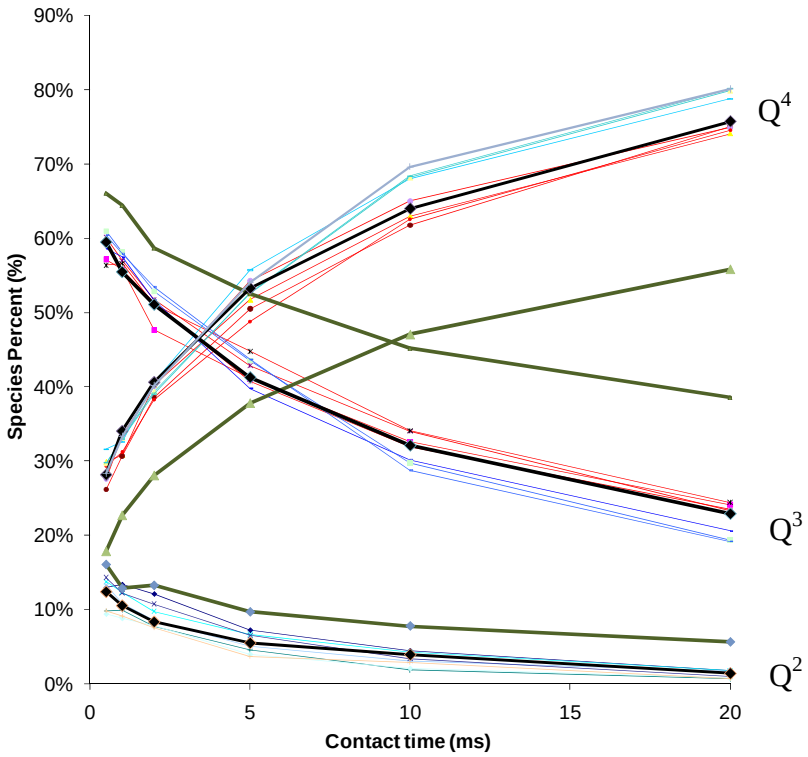

Figure 10: CP NMR data summarizing catalyst effect on degree of surface condensation. Light blue lines and the dark blue lines represent uncalcined silica spheres synthesized using the mixed catalyst system at pH = 7. Red lines represent spheres synthesized using cysteamine. Green lines represent silica formed without cysteamine or glutathione.

To conclude, monodisperse, mesoporous silica spheres have been synthesized using cysteamine and a mixture of cysteamine and L-glutathione at room temperature. The silica sphere mesopores were found to be exceptionally stable to thermal and hydrothermal treatments without surface hydrophobization or low-temperature thermal annealing. This finding was confirmed by the high relative amounts of Q^4 silica species present at the sphere surface using CP NMR. When compared to MCM-type silicas formed through standard means, it was observed that the spheres formed using cysteamine maintained a greater percentage of initial surface area than the MCM-type silicas. Cys-sphere size was also proven to be easily tunable by altering initial component ratios. These thermally stable monodisperse, mesoporous, hierarchical silica spheres have great potential for such applications as catalyst supports, separation media, and possibly sensitive particle encapsulation.

4.4 Silica Condensation at different pH Values using a Mixed Cysteamine and Glutathione Catalyst System

For encapsulation of sensitive payloads in silica, it is desirable to control the pH of the reaction mixture and access near neutral pH. In this program, amorphous silica was formed using mixtures of cysteamine and L-glutathione at a variety of different pH values and characterized using solid state NMR spectroscopy.

Silica gels and monoliths were formed using a combination of cysteamine and glutathione as catalyst in deionized water using tetraethylorthosilicate (TEOS) as precursor. It was found that the silica formed under alkaline conditions (cysteamine) was comprised of relatively monodisperse particles whereas silica formed under acidic conditions was monolithic in nature

and comprised of very fine silica particles upon drying. It is well known that silica formation is largely dependent on the pH in the reagent mixture. Acidic reaction conditions usually lead to high rates of TEOS hydrolysis and slower rates of condensation. Alkaline reaction conditions behave in opposite fashion, yielding slower rates of hydrolysis and faster condensation kinetics. At neutral pH, the condensation and hydrolysis kinetics should be more similar to those at alkaline conditions, albeit slower as it is expected that the silica solubility as well as the dissolution rate are highest at pH values around 7.

Solid state ^{29}Si MAS single pulse NMR data confirms that silica is most highly condensed at neutral pH. Single pulse NMR data was plotted against pH in **Figure 11.** It is seen that a maximum amount of Q^4 is obtained at a pH of 7. The amount of Q^4 slightly decreases as the reagent mixture pH increases into the alkaline region. As the reagent mixture becomes more acidic (pH < 5), the amount of Q^4 decreases dramatically.

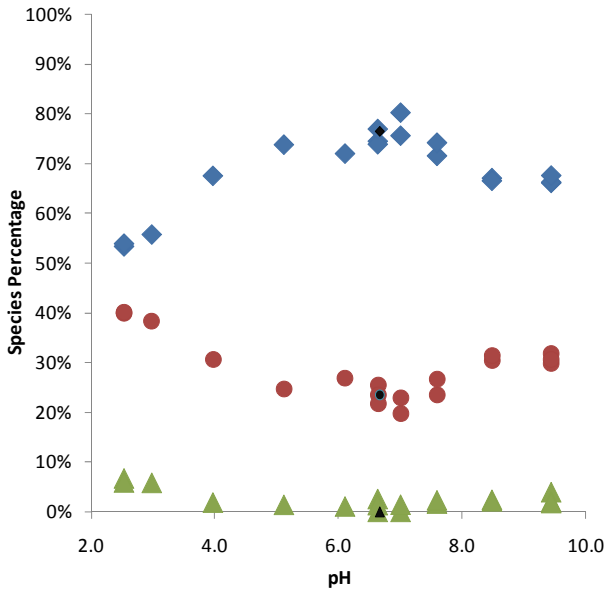

Figure 11: Silica species percentage with varying pH for the mixed cysteamine-glutathione solution and TEOS. Blue diamonds indicate Q^4. Red circles indicate Q^3. Green triangles indicate Q^2. Black symbols represent silica condensed using methionine (0.1M in 0.01M PBS)

Cross polarization (CP) ^{1}H- ^{29}Si CP NMR, as stated earlier, is capable of looking at the degree of silica surface condensation. A linear trend between species percentage and pH is noted at the silica surface. The most alkaline sample (cysteamine at a pH of 9.45) showed the largest Q^4 population, whereas the acidic samples contained the least amount of Q^4 linkages.

5. Conclusions

Unique methods for the encapsulation of biologically-derived materials within ordered mesoporous silica films, the preparation of mesoporous silica films using a biodegradable template system and the preparation of stable mesoporous silica spheres of prescribed diameters at ambient temperature using a simple one pot synthesis were demonstrated. The catalyst systems used indicate that simple, bio-inspired small molecule catalyst systems are surprisingly effective for condensing silica over a range of pH, including neutral and near neutral conditions, which suggests more complex bio-molecule systems may not be necessary to achieve silica condensation at mild conditions.

6. References

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